Improved Efficiency of Inductive Power Transfer in Misalignment Conditions with Multi Coil Design

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Abstract

In charging process of electric vehicle, a misalignment between the transmitter (Tx) and receiver (Rx) coupling structure decreases the efficiency of the wireless power transfer. In inductive power transfer system, misalignment reduces the effective coupling between the Tx and Rx coils. In this work, based on previous multiple coil structures, a new multi coil design in proposed to increase the efficiency of the power transfer. Here, a multi coil structure with two rectangular and four spiral coils is designed with the overall dimension of the coil structure 26.5 cm x 36.5 cm. The measurement shows, that for coil distance below 10.3 cm and a lateral misalignment of maximal 10 cm (27.4%), the efficiency of the designed multi coil structure is better compared to previous coil structures. However for larger coil distance or larger misalignment, the efficiency of the new coil structure deteriorates significantly.

1. Introduction

In wireless charging process of electric vehicles, the Rx coupling coil at the underside of the vehicle is positioned directly above the Tx coupling coil, which is normally installed permanently on the parking lot floor in the charging station. When the car is parked, it is possible that the position of the transmitter coil and the receiver coil is not in a perfect line (perfect alignment), there is a positional misalignment between the transmitter coil and the receiver coil due to the improperly parked car position causing the power transfer efficiency to decrease. This position shift is called lateral misalignment (Y-axis displacement or X-axis displacement) as shown in Figure 1 [1].

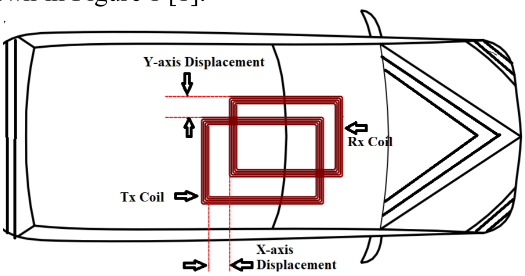

Figure 1: Coil Misalignment [1]

The orientation of the coil position is a key parameter in the design of inductive coupling systems. The lateral misalignment can be explained as the Tx and Rx coils are located in a parallel plane, separated by a distance d and the shift of the central point symbolized by Δ, as shown in Figure 2 [2][3].

In a small lateral misalignment condition, angular effects predominate, whereas in a large lateral misalignment, the lateral effect is the dominant ones [2]. In misalignment conditions, the power transmission is dependent on the coupling coefficient substantially [4].

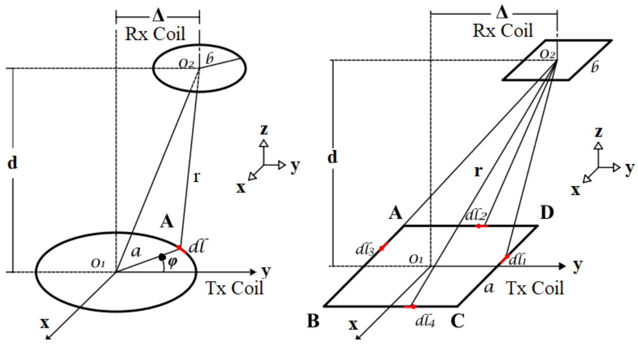

Figure 2: Lateral Misalignment [2]

This paper presents the following systematics: section 1 is introduction and background, section 2 presents the concept of *Inductive Power Transfer*, the geometry of the coils and the literature review. Section 3 presents the proposed coil geometry design, section 4 gives the experiment results and section 5 is conclusion and future work.

2. Inductive Power Transfer

Inductive power transfer is based on magnetic coupling as a power linkage from Tx coil to Rx coil. Figure 3 [5] shows a systematic model for an inductive power transfer (IPT) system. The figure reveals that some of the magnetic flux from the Tx coil intersects the Rx coil, which is located close to the Tx coil, normally less than the wavelength. The near field strength then induces a voltage across the Rx coil. The induced voltage can be used for charging wireless devices or another storage systems. The operating frequency of the inductive coupling is usually within the kilo-Hertz (kHz) range. Rx Coil must be adjusted about the operating frequency of the Tx coil in order to improve fill efficiency [6] of the system. *Claudio Carretero* in his journal said that the working frequency at IPT ranges from a few kHz to radio frequency (several tens of MHz) [7]. The advantages of the inductive coupling are easy to implementation, easy operation, high efficiency at close range (usually less than coil diameter), guarantee for security [8][9][10][11], low maintenance costs [10][12], reliable [10], has the ability to operate in dirty conditions [4][13].

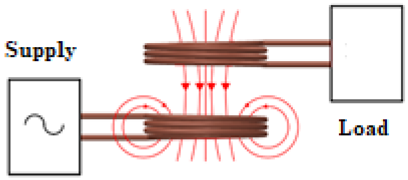

Figure 3: Inductive Coupling [5]

Generally, it can be said that *IPT* follows the Ampere's law and the Faraday's inductive law. The Ampere's law, or more generally the Biot Savart's law, explains the distribution of the magnetic field vector in the space, especially around the coil structures. The relationship of the direction of the current to the loop with the direction of the resulting magnetic field follows the rule of the right hand (or the screw) where the thumb shows the direction of the current, while the other finger shows the direction of the magnetic field. The Faraday's law or the induction law gives the relationship between the induced voltage and the change of the magnetic flux through the Rx coil to the time.

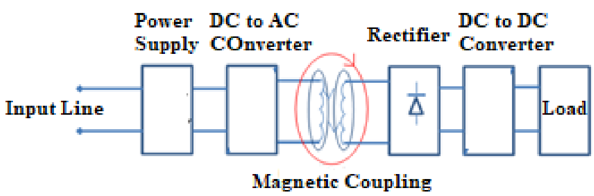

Figure 4: Block Diagram of IPT system [5]

In the *IPT* System (Figure 4), generally consists of three main components: power supply, two coupled coils, rectifier and DC / DC converter. The power supply produces sinusoidal current, with a frequency typically within the kHz. The power transfer happens through inductive coupling from the Tx coil to the Rx coil. These two coils are not always identical, they can have different shapes and dimensions. The rectifier may be required to transform the high frequency AC voltage to DC voltage if the load to be powered is a DC load. Moreover, an additional DC/DC converter can be required to provide a regulated input DC voltage to the load [5].

There are many studies about power transfer efficiency in wireless power transfer systems. The studies used different frequencies and coil designs, and they observed the efficiency of power transfer in perfect alignment and in misalignment conditions. The difference in frequency and coil design leads to difficulties in comparing one design to the others. For example *Kalwar* et al [4] (2016) introduced the IPT coil design with the name QDQ (Quad D Quadrature) by combining four small circular coils placed on a large rectangle coil with a resonant frequency of 33 kHz and a distance between Tx and Rx coils of 15 cm. This design is made identically between Tx coils and Rx coils. *Kuzey* et al [14] (2017) made a coil design with rectangle shape with Tx 60 cm x 100 cm coil dimension and Rx 60 cm x 60 cm coil size with 17.702 kHz resonance frequency.

2. 1 Coil Geometry Design

In [4] it is mentioned that the coil of the spiral circle have a good coupling but poor tolerance at misalignment condition. The spiral circle coil have the mutual induction higher than the rectangular geometry shape at perfect alignment, but the performance during misalignment conditions, the rectangular coil is better than spiral circle. Therefore, rectangular geometry is more common in electric Vehicle applications.

Based on the Neumann's equation [15] to calculate the magnitude of the mutual inductance between two circle coils with number of turns (N_{Tx} and N_{Rx}), radii r_1 (m) and r_2 (m), permeability μ (H/m) and the gap of the coil d (m) can be computed as Eq. 1.

$$M = \frac{\mu \pi N_{Tx} N_{Rx} r_1^2 r_2^2}{[(r_1+r_2)^2+d^2]\sqrt{(r_1+r_2)^2+d^2}} \quad (1)$$

If coil inductance (H) is L_{Tx} and L_{Rx}, the magnetic coupling coefficient formula is as in Eq. 2:

$$k = \frac{M}{\sqrt{L_{Tx} \cdot L_{Rx}}} \quad (2)$$

2.1.1 Flat Spiral Coil

For Flat spiral coil [16], as shown in Figure 5, we can calculate L (Inductance), R (Resistivity), C (Capacitance), Q (Quality factor) value by considering the outside diameter (Do), number of turns (N), the distance between the windings (p) and the diameter of the wire (w), the inner diameter (Di), the average value of radius (a), length of wire (l) and the winding width (c) must also be considered, as illustrated in Figure 6. All these quantities are in meters.

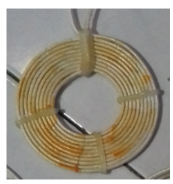

Figure 5: Flat spiral coil

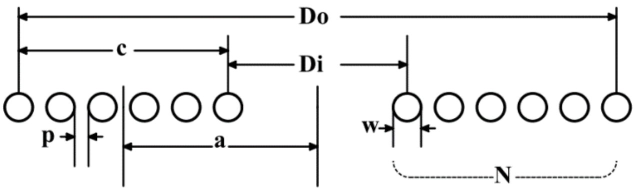

Figure 6: The cross-sectional view of flat spiral coil [16]

The Self-Inductance on this coil is obtained from the Wheeler's formula,

$$L\,(H) = \frac{N^2(D_o-N(w+p))^2}{16D_o+28N(w+p)} \times \frac{39.37}{10^6} \qquad (3)$$

The self-capacitance depends on the relative permittivity coil wire, the diameter of each coil, number of turns N, and the distance between windings. Usually, the self-capacitance magnitude on the order of a few pF and this is very small when compared with the tuning capacitor for resonance IPT. It is, therefore, necessary tuning capacitance of a coil inductance and defined in terms of the resonant frequency as formulated as follows:

$$C\,(F) = \frac{1}{(2\pi f)^2\ L} \qquad (4)$$

Resistance:

$$R_{DC}(Ohm) = \frac{1}{\sigma\pi(\frac{w}{2})^2}\ ,\ \delta = \frac{1}{\sqrt{\pi f\sigma\mu_0}} \qquad (5)$$

$$R = R_{DC}\frac{w}{4\delta} = \sqrt{\frac{\pi f\mu_0}{\sigma}}\ \frac{N(D_o-N(w+p))}{w} \qquad (6)$$

Quality Factor:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{39{,}37}{10^6}\sqrt{\frac{f\pi\sigma}{\mu_0}}\ \frac{wN(D_o-N(w+p))}{8D_o+14N(w+p)} \qquad (7)$$

This formula is used for optimization of the coil design for a high Q and ensure resonance at the desired operating frequency [8].

2.1.2. Rectangular Coil

In [14], *Kuzey* et al presents a formula for rectangle-shaped coils, as given in Figure 7 with the following equation:

$$r_1 = \sqrt{\frac{N_{Tx}S_{Tx}}{\pi}}\ ;\qquad r_2 = \sqrt{\frac{N_{Rx}S_{Rx}}{\pi}} \qquad (8)$$

For the coil resistance's formula is as equation 9 where is ρ_{cu} for copper, a_1 and b_1 is dimension of coil.

$$R_{Tx} = \rho_{cu}N_{Tx}\frac{2(a_1+b_1)}{S_{Tx}} \qquad (9)$$

To calculate the self-inductance of Tx and Rx coil, we used equation 10 and 11:

$$L_{Tx} = \frac{\mu_0}{\pi}N_{Tx}^2[a_1 ln\frac{2a_1b_1}{r_1(a_1+\sqrt{(a_1^2+b_1^2)})} + b_1 ln\frac{2a_1b_1}{r_1(b_1+\sqrt{(a_1^2+b_1^2)})}$$

$$-2(a_1 + b_1 - \sqrt{a_1^2+b_1^2}) + 0.25(a_1+b_1)] \qquad (10)$$

$$L_{Rx} = \frac{\mu_0}{\pi}N_{Rx}^2[a_2 ln\frac{2a_2b_2}{r_2(a_2+\sqrt{(a_2^2+b_2^2)})} + b_2 ln\frac{2a_2b_2}{r_2(b_2+\sqrt{(a_2^2+b_2^2)})}$$

$$-2(a_2 + b_2 - \sqrt{a_2^2+b_2^2}) + 0.25(a_2+b_2)] \qquad (11)$$

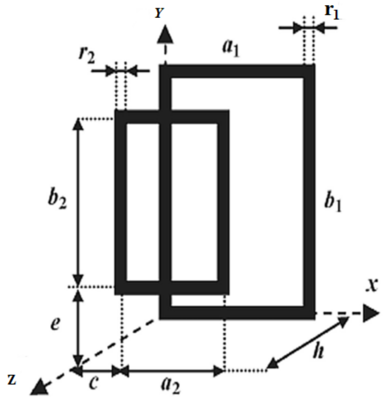

Figure 7: Rectangular Coil [14]

2.2. Efficiency

The efficiency of *IPT* depends on the quality factor of each coil Tx and Rx. The values of the quality factor can be calculated by assuming working independently for each coil. Moreover, the efficiency depends significantly on the tightness of the coupling between the coils, which is symbolized by the coupling coefficient k [9].

In theory, the maximum efficiency (PTE_{max}) for IPT configuration that can be obtained can be expressed as a function of the quality factor of the coil (Q_{Tx} and Q_{Rx}), and the coupling coefficient (k). PTE_{max} only characterized by the design of the coil (specify Q) and the relative geometry between coils (determine k). Therefore, PTE_{max} formula can be directly used for analysis coil design and geometry [10].

$$PTE_{max} = \frac{k^2Q_{Tx}Q_{Rx}}{1+\sqrt{1+k^2Q_{Tx}Q_{Rx}}} \qquad (12)$$

The maximum system efficiency is obtained by optimal inductive coupling coefficient, appropriate compensation topology, and operating at the same resonant frequency (f_0). The same resonant frequency can be achieved if the inductive reactance is equal to capacitive reactance so that the equivalent impedance is equal to the circuit resistance [14],

$$f_0 = \frac{1}{2\pi\sqrt{L_{Tx}\,C_{Tx}}} = \frac{1}{2\pi\sqrt{L_{Rx}\,C_{Rx}}} \qquad (13)$$

L_{Tx} and C_{Tx} is the equivalent value of the inductive reactance and capacitive reactance of the design on the transmitter coil while the L_{Rx} and C_{Rx} is equivalent to the value of the inductive reactance and capacitive reactance of the design on the receiver coil.

2.3. Research Positioning

In 2014, *Benjamin H Water* et al [16] presented an equation for calculating the ratio and size of circle coils (equations 3 to 7). This equation is used to accurately calculate self-inductance, capacitance, resistance, quality factor in flat circle spiral coil. To validate the equation, *Benjamin H Water* experimented with pitch variation and number of turns, of the same diameter as shown in Figure 8.

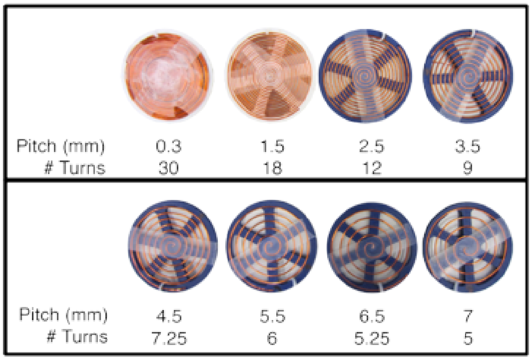

Figure 8: Variation of pitch distance and number of turns [16]

Budhia et al [10] explained that Circular couplers topology is the most commonly used in the literature; But essentially they have a limited coupling. Flux patterns they certainly limit the operational air gap and tolerance to misalignment. *Budhia* experimented by comparing the topology circle compared to the DD topology (Double D) which is double-lined circle topology, as well as with DD-DDQ combined topology (double D-Quadrature Coil) which is adding rectangle coil to circle coil to solve coupling's problem. This test uses a distance between 20 cm coil and 20 kHz frequency. The result is the DD-DDQ topology can increase the charging area 5 times more than the circle topology for the same coil area.

Kalwar et al [4] used QDQ (Quad D Quadrature) to maintain a high coupling coefficient during a reasonable misalignment condition. The QDQ design uses 4 mutually adjacent circle coils and a rectangle coil and between the Tx and Rx coils is identical to capture the maximum flux in any position. This experiment uses a resonance frequency of 33 kHz and a distance between 15 cm coils. The coil design between Tx and Rx is made identical. *Kalwar* experiment for misalignment condition reaches a position 50% of the total area of the coil.

Kuzey et al [14] proposed coil design with rectangle shape but coil size Tx 60 cm x 100 cm and coil size Rx 60 cm x 60 cm with resonance frequency 17.702 kHz and the distance between coil 20 cm as in Figure 7. *Kuzey* also conducts tests for angular misalignment conditions.

Zhichao Luo [17] compared the performance between square coils with circular coils. Both coils are made with the same parameters. A square coil with dimensions of 600 mm x 600 mm, whereas a circular coil is made with a radius of 300 mm or a diameter of 600 mm, other parameters such as pitch, wire diameter, number of turns is made equal. The resulting square-shaped coil produces mutual inductance and coupling coefficients higher than the circular coil so that the rectangular coils prove to be a better choice for WPT systems.

3. Proposed Coil Geometry Design

This paper used three coil designs. We redesigned the coil structure given by the reference [14] with identical Tx and Rx coils and called it 1st design. The 2nd design is a redesign of the coil structure as given by reference [4], whereas the 3rd design is a new coil structure proposed in this work. All of design as illustrated in Figure 9.

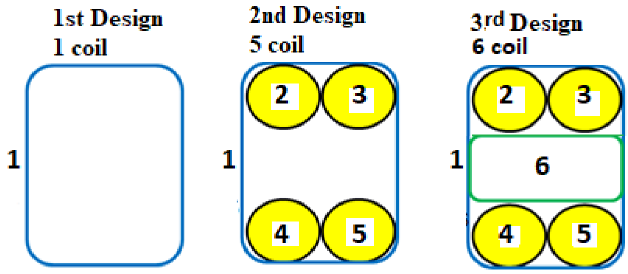

Figure 9: Coil Design Geometry

Coil number 1 is made with dimensions of length and width, for the outer dimension is 36.5 cm x 26.5 cm, while the inner dimension is 30 cm x 20 cm. For 2,3,4 and 5 coils are made identically with an outer diameter of 9.8 cm and an inner diameter of 4.74 cm. While for the outer dimension coil number 6 is 10 cm x 20 cm. All coils are made with the same litz wire with diameter of wire 1.15 mm and number of turns each coils is 10 turns. All of these coil designs are tested with a maximum power of 4.6 watts. All of coils parameter data gived in table 1.

Table 1: Coil Dimension

Max power	4.6	watt
Number of strand	32	pcs
Diameter of strand	0.19	mm
Total wire diameter (w)	1.15	mm
Total wire diameter + Insulation	2.53	mm
The distance between wires (p)	1.38	mm
Wire + Insulation's Area (S_{Tx} ; S_{Rx})	5.024	mm^2
Coil 1		
Outer length	36.5	cm
Outer width	26.5	cm
Inner length	30	cm
Inner width	20	cm
Number of turn (N)	10	

Coil 2= Coil 3= Coil 4= Coil 5		
Outer diameter (D0)	9.8	cm
Inner diameter (Di)	4.74	cm
Number of turn (N)	10	
Coil 6		
Outer length	20	cm
Outer width	10	cm
Number of turn (N)	10	

In this work a rectangular coil (coil number 6) was added to the middle of the previous design to increase the power transfer performance at a misalignment condition. This is based on [4] which states that the rectangular coil have a transfer performance better than circle coil at misalignment condition.

From the equation (3), (8), (10) and (11), the calculation of the inductance value in coil number 1 is 86.126 µH, coil number 2,3,4,5 each has the value 9.141 uH, for coil number 6 the value of L is 34.555 µH so the total of the inductance is 157.245 µH. The total inductance of the measurement is 150 µH. The results of the inductance calculation and the C value used, can produce a resonance frequency of 25.619 kHz on the Tx coil, and on the Rx circuit arranged with the same frequency.

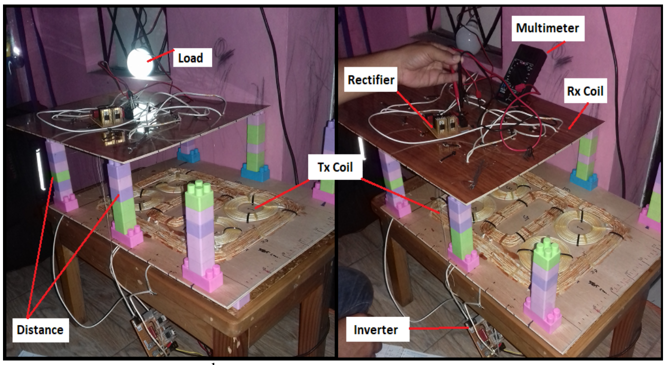

Figure 10: 3rd Coil Design and Measurement

Figure 10 shows the full inductive power transfer systems built in this research. The measurement gives a periodic signal with the fundamental frequency of 35.088 kHz produced by the inverter. This frequency is above the resonance frequency of coil structure. Behind the Rx coil, the AC voltage is converted to DC with a rectifier. Measurement of efficiency in this work is carried out by comparing the DC output power at load to the DC input power. The result of determining the amount of load impedance obtained by measuring the output stage in open circuit condition and the current in short circuit condition at load point.

It is expected that the inverter can be used for all coil designs, all fixed coil used in an attempt to meet the value of the inductor L2 and L3 respectively 150 µH as shown in Figure 11. On the 1st of design, there is only one coil used for power transfer process, therefore the other coil remains installed and functioning as a resonator. Likewise with the 2nd design, when only 5 coils are used for the power transfer process, 1 remaining coil is still installed as a resonator.

In this research, all the coils were installed in series electrically.

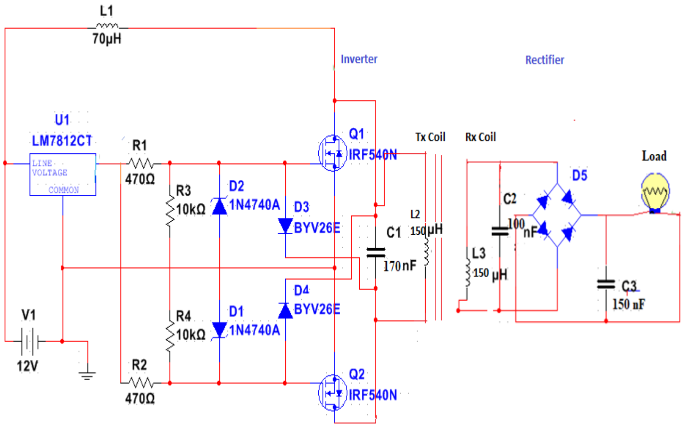

Figure 11: Full circuit schematic of the research

4. Experiment Result

Table 2 and Figure 12 gives the efficiency of the power transfer as function of distance at a perfect alignment. It is found that at the coil distance of 2.8 cm to 13.9 cm the efficiency of 3rd design is better than the two other designs from the highest value of 48.9% and decreases to 16.5%. The declining value of efficiency due to the distance coil increased fit to equation (1) (2) and (12) where the mutual inductance is inversely proportional to the distance of the coil, magnetic coupling coefficient proportional to the mutual inductance and PTE_{max} proportional to magnetic coupling coefficient so higher mutual inductance values cause increased efficiency.

Table 2: Efficiency at a Perfect alignment

Coil Distance (cm)	1st Design	2nd Design	3rd Design
2.8	44.9%	47.4%	48.9%
4.6	45.8%	42.0%	48.4%
6.5	35.6%	37.0%	41.2%
8.4	27.6%	30.7%	35.2%
10.3	22.1%	22.9%	26.9%
12.2	15.5%	19.7%	22.3%
13.9	11.1%	15.6%	16.5%

At the misalignment conditions (X-axis displacement), Figure 13 shown that the misalignment between 0 cm up to 10 cm (misalignment of 0% -27.4%) for a coil distance of 2.8 cm, 4.6 cm, 6.5 cm and 8.4 cm, the 3rd design produces the highest efficiency and its value coincides with the 2nd design when the coil distance is more than 10.3 cm. In a X-axis displacement condition of more than 10.3 cm, the efficiency of the 3rd design decreases as it is influenced by coil number

6 on Tx parallel to coil number 2 and 3 in Rx, where there is a different magnetic field direction so the resultant drop.

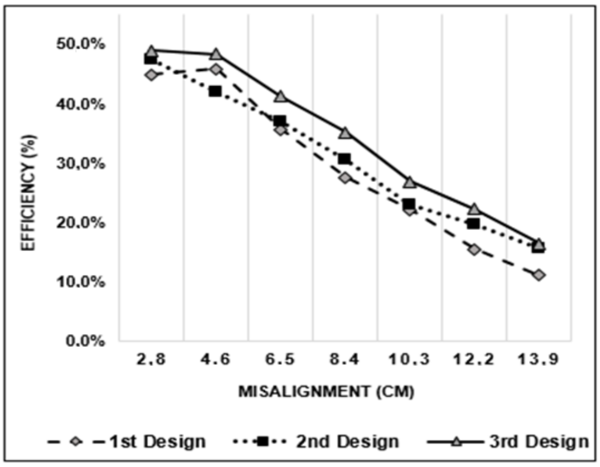

Figure 12: Efficiency at a perfect alignment

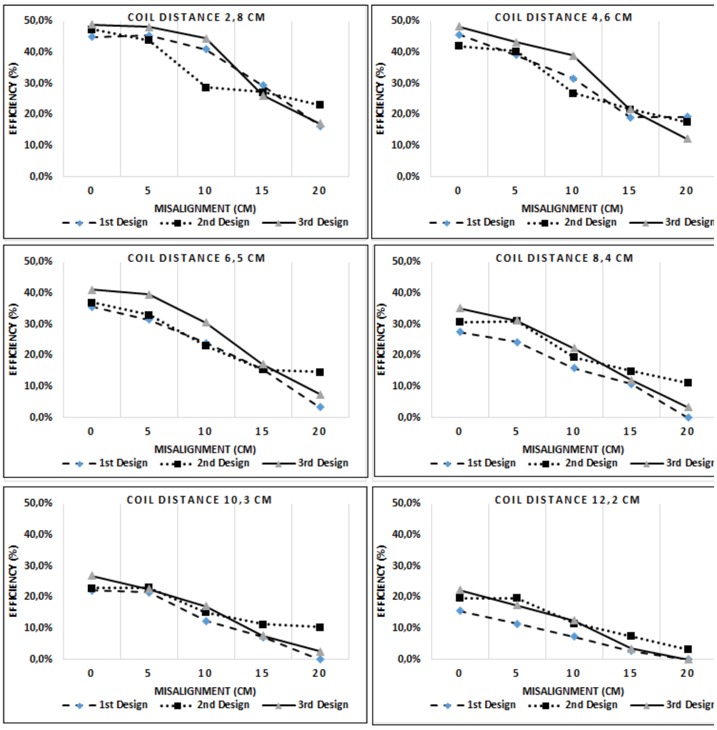

Figure 13: Efficiency for several X-axis displacements

5. Conclusions and Future Work

Comparison between the results of three coil designs gave, generally for perfect alignment conditions, 3rd design is the best from others for all coil spacing. While the misalignment up to 10 cm (27.4%), the 3rd design performance still shows the best value up to the coil distance of 10.3 cm. At a coil distance above 10.3 cm and a misalignment above 10 cm, the efficiency of 3rd design slightly decreases below 2nd design, but is still high compared to 1st design.

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